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An LTCC 94 GHz Antenna Array

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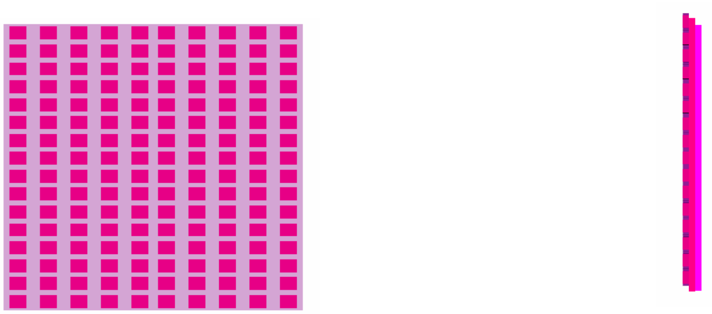
Abstract
An antenna array is designed in low-temperature cofired ceramic (LTCC) Ferro A6M™ for a mm-wave application. The antenna is designed to operate at 94 GHz with a few percent bandwidth. A key manufacturing technology is the use of 3 mil diameter vias on a 6 mil pitch to construct the laminated waveguides that form the beamforming network and radiating elements. Measurements for loss in the laminated waveguide are presented. The slot-fed cavity-radiating element is designed to account for extremely tight mutual coupling between elements. The array incorporates a slot-fed multi-layer beamforming network.

Introduction
There have been recent trends in detector applications that require operation in the mm-wave frequencies [1,2]. To operate systems and antennas successfully in these high frequency bands, a low-loss dielectric and high conductivity metallization is required. We describe in this paper an antenna array designed to operate at 94 GHz. The antenna uses laminated waveguide [3] constructed in low-temperature cofired ceramic (LTCC) Ferro A6M. Ferro A6M has a dielectric constant of 6.2 and a loss tangent nominally of 0.003 at 94 GHz. The conductor used in the Ferro material technology system is a gold paste having a conductivity of 3mOhm/square.

The antenna array is comprised of two major components: The beamforming network, and the radiating elements. The antenna architecture was constrained by limiting predefinied footprint requirements. This constraint dictated that the beamforming network be constructed beneath the radiating aperture as shown in Figure 1a.. Immediately beneath the radiating elements is a two layer beamforming network which couples to 160 slot-fed cavity radiating elements as illlustrated in Figure 1b.



a) b)

Figure1.a) Front view of array, b) side view of array illustrating multilayer structure of antenna

Design Methodology

The methodology for designing the antenna array is to divide the array into its major components and transitions, optimize each component and transition and subsequently reassembling the entire system for resimulation and eventual fabrication.

As one follows the signal from the beamforming network to the radiating element, one encounters the major

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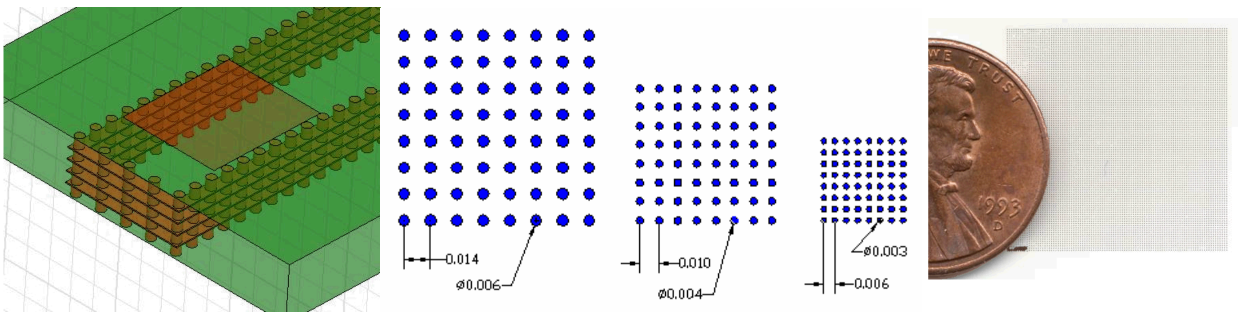
transitions: the WR-08 to laminate waveguide transition, the T-junction transition, the right angle bends, the transition from the first layer to the second layer of the beamforming network, and finally the transition to each laminated waveguide slot-coupled to the radiating elements. The radiating antenna element was designed in an array environment using periodic boundary conditions.

Laminated Waveguide

A key requirement in the selection of the material technology is the isolation requirements for the laminated waveguide in the feed network. Figure 2a illustrates the construction of a laminated waveguide (LWG). The LWG is rectangular dielectric-filled waveguide using vias for the side walls and solid planes for the top and bottom walls. The via size and pitch must be sufficiently small to meet the stringent requirements for isolation between the inside of the LWG and outside of the LWG. For this application the vias are 3 mils in diameter on a 6 mil pitch.

These via sizes and pitches are beyond the standard design rules typically used in lower frequency applications. In Figure 2 b, c, d, we compare our via technologies. In our typical via technology for LTCC, the vias have a 6 mil diameter and are located at a 14 mil pitch. The minimum design rules have 4 mil diameter vias on a 10-mil pitch. The advanced via processing technology required for this antenna has 3 mil diameter vias on a 6 mil pitch.

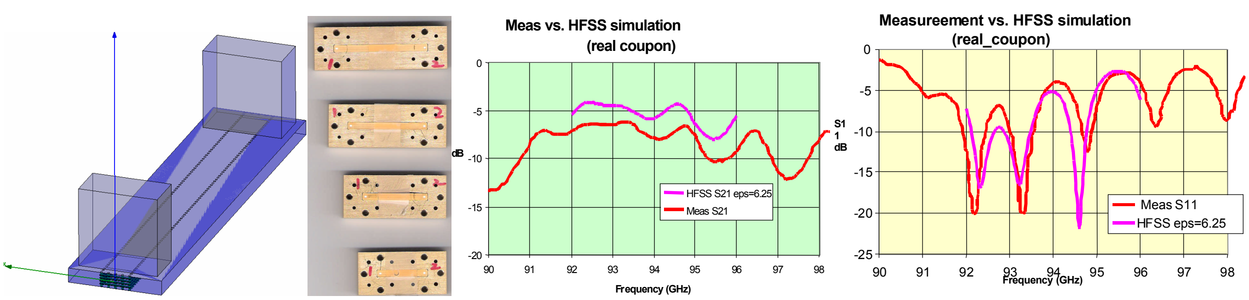


a) b) c) d) e)

Figure 2. a) Laminated waveguide, b) typical via design rules, c) minimum via design rules, d) advanced via design rules. e) 10000 vias punched and filled on 1 layer of LTCC tape.

In Figure 2e we illustrate the punching and filling of 10000 vias on 1 layer of LTCC tape. Without careful handling, tool wear can lead to slight tape tearing as shown in the lower left hand corner of the via grid.

To measure the loss in the LWG, several coupon structures were simulated and measured. Figure 3a shows the HFSS model of a 1 inch LWG coupled to WR-08 waveguide at both ends. The model incorporates the nominal material values. The LWG structure was fixtured as shown in Figure 3b.



a) b) c) d)

Figure 3. a)HFSS model of LWG for insertion loss simulation., b) Laminate waveguides in test fixture, c) measured vs. simulated insertion loss for 1 inch long LWG, d) **m**easured vs. simulated return loss for 1 inch long LWG

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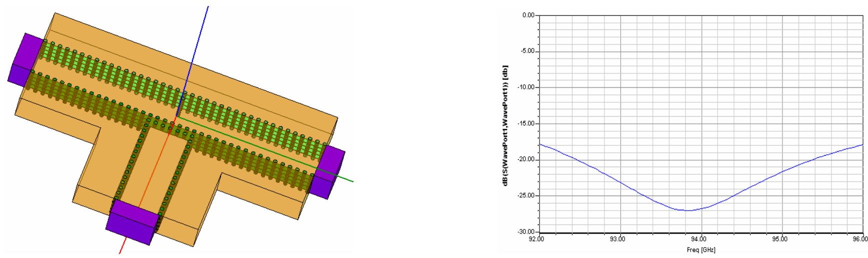
Figure 3c and Figure 3d show the comparison between simulation and measurement for insertion loss and return loss, respectively. The simulated insertion loss has similar characteristics as measured data, but is under predicting loss by 2 to 3 dB. The simulated return loss on the other hand agrees extremely well with measured data.

T-junction
The major transition in the beamforming network is the 3 dB power divider, or the T-junction, as shown in Figure 4a. The fine sizes of the via allows the necessary resolution for via placement to achieve good return loss as shown in Figure 4b.



a) b)

Figure 4. a) HFSS model of T-junction power divide, b). Return loss for T-junction power divider.

Serial feed
To feed the antenna cavities a 1x5 serial feed is designed. The serial feed is designed to couple energy such the array is uniform in amplitude. The coupling is accomplished by controlling the position of the via post and the arm irises. The losses are accounted for by adjusting the coupling values accordingly. The loss of the ceramic and conductor gold paste is accounted for in the calculated values of the coupling values at each branch point of the serial feed. Figure 5a shows an MWS model of a 1x5 serial feed arm. The coupling from the main arm to each arm is designed to be close to -7.6 dB at port 1, -6.5 dB at port 2, -5.1 dB at port 3, -3.2 dB at port 4 and 0 dB at port 5.

The simulated results of the coupling from 90 to 98 GHz is shown in Figure 5b. Across this band of interest the variation in coupling is less than +/- 0.5 dB

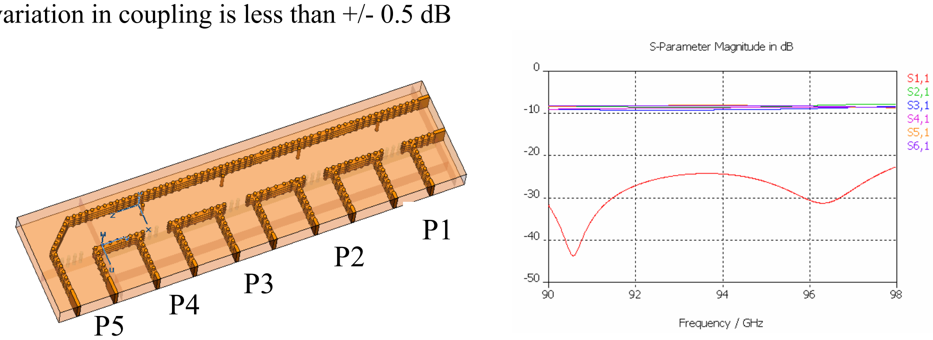
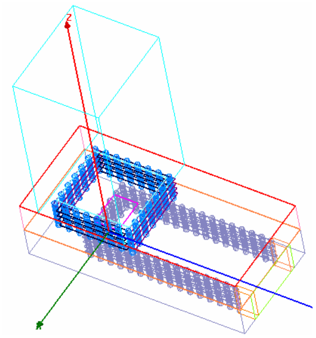


Figure 5a. MWS model of 1x5 uniform-amplitude serial feed, b) Return loss and coupling values at ports for single serial feed

Antenna radiating element
The key aspect of the array design is to design the antenna in the array environment. Designing the radiating element in an infinite array as supported by full-wave EM simulation tools by implementation of a periodic boundary condition. An HFSS model of a single radiating element shown in Figure 6a. The element is fed by a short section of LWG. The element radiates into freespace with periodic boundary conditions simulating radiating in an infinite array environment.



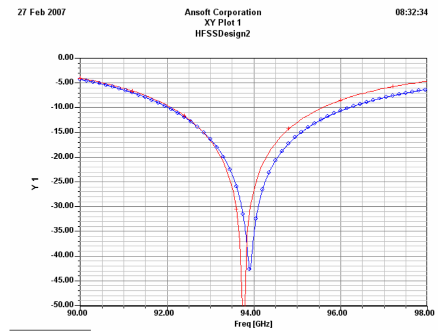


Figure 6. a) HFSS model of LWG feeding slot-fed cavity antenna element in infinite array environment, b) Return loss of slot-fed cavity radiating element in infinite array environment.

The return loss of an element radiating in an infinite array environment is shown in Figure 6b. A comparison is made between using solid walls in the model as opposed to the via-walled case. Retuning for the via-walled case was required in order to reacquire the solid-wall performance.

Figure 7a shows a section of the array aperture. The radiating element pitch in the x and y direction were optimized for beam-tilt arising for phase taper across serial feed network

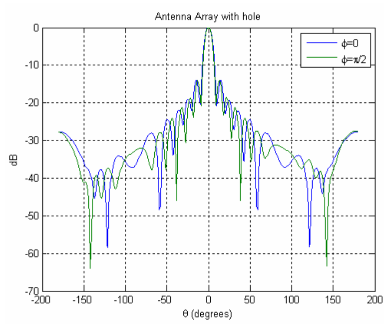


Figure 7a. Array aperture radiating elements, b) Antenna pattern for 94 GHz antenna array.

In Figure 7b, we compute the antenna pattern for the antenna array. Sidelobe levels are at –13 dB as expected for uniform illumination. The beam width is nominally 15 degrees and the gain is 18.2 dBi.

Conclusions

We have designed the beamforming network and antenna-radiating element for a 94 GHz planar array. New processes were developed to manufacture and process 3 mil vias on a 6 mil pitch for Ferro A6M. Coupon measurements agreed well with full-wave simulations. Full-array measurements agreed well with the simulations and met the system requirements.

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